Application of New Techniques of Signal Processing for Detection of Wear Mechanisms in Turning of AISI 4340 Using Acoustic Emission

Luis Henrique Andrade Maia (✉ luismaia@pucminas.br)

Pontificia Universidade Catolica de Minas Gerais <https://orcid.org/0000-0002-5875-5049>

Alexandre Mendes Abrão

Federal University of Minas Gerais

Wander Luiz Vasconcelos

Federal University of Minas Gerais - UFMG

Jánes Landre Júnior

Pontifical Catholic University of Minas Gerais - PUC Minas

Álisson Rocha Machado

Federal University of Uberlândia - UFU

Wisley Falco Sales

Federal University of Uberlândia - UFU

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Abstract

In this study, the short-time Fourier transform (STFT) technique was used to determine the wear mechanisms acting on uncoated and AlCrN-coated carbide tools and their variations during the machining process. To this end, tensile tests were performed on hardened AISI 4340 steel to characterize the acoustic emission (AE) signals and subsequently isolate the steel deformation and fracture mechanisms from the signs of tool wear during the steel turning. Machining tests were carried out using the following parameters: cutting speeds of 150, 200 and 250 m/min and feed rates of 0.10 and 0.20 mm/rev. The results demonstrate that AE signals in conjunction with STFT analysis can be used to identify abrasive wear, adhesive wear and other phenomena that occur during cutting.

Introduction

Physical phenomena inherent in the cutting of metals, such as plastic deformation and work hardening of the work material, along with the process of chip formation, lead to tool wear, which involves several mechanisms [1]. Thus, in the metal-mechanical industry the exact moment for tool change is still difficult to determine and has been the target of several studies within the scientific community. Some of these studies have involved the use of continuous monitoring techniques.

Acoustic emission (AE) can be applied in indirect monitoring and its use is already widespread, mainly in the monitoring of static equipment and pressurized vessels. Acoustic emission is the power released by a body when its initial form is altered. Thus, corrosion, conformation, wear and shearing, along with tensile and compressive stresses, are the mechanisms that generate acoustic emission in a body[2]. However, several mechanisms and phenomena involved in the cut that need to be taken into consideration in the application of the AE technique are still not well understood. The frequencies at which different phenomena occur, such as the movement of dislocations, coalescence of voids and formation of twins, are not well defined. In addition, the contribution of temperature and wear as well as friction processes at the chip-tool-workpiece interfaces must be considered.

Some characteristics of the acoustic emission signal are sensitive to the wear mode. For example, a high signal intensity is typical of abrasive wear rather than adhesive wear or fatigue wear[3].

The basic premise of acoustic emission in the friction of a tribological pair is that when two surfaces are in contact there are macro and micro processes involved in the structural changes, such as plastic deformation, failure (formation and development of micro and macrocracks), phase transformations, formation and destruction of adhesive bonds, corrosion and oxidation. All of these physico-mechanical and chemical-mechanical processes are sources of acoustic emission [4]. In order to interpret acoustic emission signals in tribological processes there is a need to understand how the elastic interaction of surface roughness is converted into acoustic emission signals, in order that these can be separated or eliminated from the signals generated by the wear mechanisms [4].

Pandiyan and Tjahjowidodo [5] studied the wear mechanisms in abrasive belt grinding process using STFT to detect contact variations. The authors state that the rubbing, ploughing and cutting mechanisms excite a range of 25 kHz to 350 kHz, and the range of 125 kHz to 350 kHz correspond to the cutting mode, while the range of 25 kHz to 125 kHz are derived from rubbing and ploughing modes.

On a pair of contact surfaces subjected to a displacement, in which there is friction, acoustic emission signals oscillate slightly. The tribological profile of the pair changes due to heating, the formation of oxides and a change in the tension state.

Kuntoğlu and Sağlam [6] investigated the ability of five types of sensors to measure tool wear. Cutting forces, vibration, acoustic emission, temperature and current were measured during the turning of AISI 5140 steel with coated cemented carbide tools. Considering the graphic investigation, the successes of the sensors in the detection of progressive flank wear and tool break age were investigated. According to the results, the authors report that the signals of temperature and acoustic emission were the most effective in correlating with flank wear.

The wide range of frequencies of the acoustic emission signals (10 kHz to 1.6 MHz) means that errors can occur when determining certain events. This masks a series of phenomena and leads to false conclusions concerning the signal [2]. A better knowledge of the frequency ranges in which an event occurs, coupled with the boundary conditions, could lead to more accurate results and satisfactory conclusions.

Hase et al. [7] studied the characteristics of acoustic emission signals and correlated them with several phenomena, including wear mechanisms (Fig. 1). Abrasive wear covers a large frequency band (200 kHz to 1 MHz), but the peaks are well characterized and can serve as a basis for identifying which mechanism prevails in an experiment. The propagation of cracks appears in the range of 100 kHz to 700 kHz and therefore overlaps with the excitation generated by abrasive wear. Slip excitation occurs within a narrowband (25 kHz to 110 kHz) and overlaps with that of mild adhesive wear and particle interactions. The other mechanisms have very characteristic peaks and promote much lower excitation bands than abrasive wear.

Lu et al. [8] studied the efficacy of the STFT, wavelet, and Hilbert-Huang transform for the analysis of AE signals in the carbon fiber compression test. To this end, the authors imposed a compression speed on a specimen measuring 100 mm × 20 mm × 2.5 mm. The authors stated that the STFT and the wavelet did not adjust to the point of causing a variation in the excitation in terms of time and frequency (known as pitching) and the Hilbert-Huang transform was more effective for monitoring in the test. They further concluded that the fracture of the carbon fiber generated excitation at a frequency of 275 kHz while the cracks in the matrix generated excitations in the frequency range of 175 kHz to 200 kHz.

Geng et al. [9] used the acoustic emission to characterize wear and friction in steel contacts in dry slips. The authors found that the behavior of wear is reflected in the excited frequencies being indicated by increased energy and widening of peaks. They also demonstrated that the rms and ae energies integrated

are the volume of proportional wear, provided that the wear mechanism remains constant (a change in gradient was observed in the transition from abrasive plastic wear to oxidative wear). Since the EA can be measured continuously, it can provide an in-situ way to monitor wear, and this will be evaluated in the future.

Marinescu and Axinte [10] used the STFT technique to detect failures in mill-machined parts with multiple cutting edges simultaneously. The authors milled Inconel 718 with five carbide inserts coated with TiAlN + TiN. The tests were performed varying the radial depth of cut so that the number of cutting edges in contact with the workpiece varied, while changing the axial depth of cut so that it generated practically the same signal amplitudes. The AE signals demonstrated by STFT were extremely sensitive to the excitation variation generated by the number of sharp edges during cutting. The authors also generated a defective surface by imposing an insert with sharp wear on the tool and analyzed the STFT of the operation. They concluded that with the use of the technique to monitor the milling process, failures in the machined parts could be identified.

König et al. [11] monitored and classified, through machine learning, wear on rolling bearings using the acoustic emission technique. The signals were analyzed so that anomalies were detected in the operation of the bearings. The authors reported that it was observed that there was success in detecting faults due to lack of lubrication and abrasive wear by three bodies. In addition, they observed that critical operating conditions generated spectra in the range of 40 kHz to 700 kHz.

Filippov et al. [12] studied vibrational response and acoustic emission in turning using without-the-have tools. They verified the response of the acoustic emission to the vibrational profile of the workpiece and observed that the high amplitude vibrations also increase the amplitude of the signals and alter the type of AE signal. In addition, the authors observed that the signal energy changes with the vibrational load, and this impacts the machined profile and chip shape.

Neslu šan et al.[13] studied the detection of ceramic tool breakage during hard turning using EA signals. They analyzed various types of sensors and studying various parameters, tried to correlate with the cutting process itself. They demonstrated that the type of sensor relates to the phenomenon that one wants to observe. In addition, they noticed that the technique was not able to analyze the variations of wear in the tool.

Maia et al. [14] developed a new technique to monitor tool wear using AE signals and to determine the tool life in machining with carbide inserts. A high-pass filter was used and the contribution of the filtered signal along with the amplitude of the modulated signal were associated, and the autocovariance was represented by the power spectral density (PSD) technique. The technique was found to be very sensitive to the level of wear of the tool, in addition to detecting the mechanisms involved. A significant difference is that in the study reported herein only the filtered signals were considered and these were processed using the STFT technique, which shows the temporal variation of the frequencies and confirms that the mechanisms of wear act discretely on the tool over time.

The purpose of this study was to investigate the acoustic emission signals and to use them to identify the tool wear mechanisms and characterize the tool life. The STFT technique is used to show that several mechanisms acting together and/or alternately.

Methodology

The deformation curves for the AISI steel were obtained from tensile tests carried out on a universal machine EMIC model DL 20000MF, for which the maximum load capacity is 200 kN. The machine is of the single-phase type, electromechanically driven by a variable speed motor and ball screw, which allows speeds of 0.01 mm/min to 50 mm/min. The force measurement was performed by means of load cells according to the ISO7500-1 standard. The displacement is measured by the optical sensor with a resolution of 0.01 mm and a maximum stroke length of 220 mm. The instrumentation is built into the machine cabinet and designed to work in conjunction with a microcomputer.

The turning tests were performed on a Centur CNC lathe (model 30D) manufactured by Indústrias ROMI SA, with a power of 7.5 kW and a variable spindle speed range of 4 to 4000 rpm, maximum permissible diameter of 200 mm and maximum workpiece length of 1000 mm. The numerical control of the machine is the MACH 9.

The AISI 4340 steel parts with 46 ± 1 HRC (474 HV) were 300 mm long with a diameter of 70 mm and they were machined in two passes (150 mm each).

AISI 4340 steel has high hardenability and good forge properties, but with a low level of machinability and weldability. It is used in the manufacture of axles, connecting rods, crankshafts and parts with a high mechanical demand, in the aerospace, automobile, machinery, and equipment industries, etc.

The mechanical properties of the material were measured by the tensile test, which are outlined in Table 1.

Table 1. Mechanical Properties of the AISI 4340 steel.

Yield Stress (MPa)	UTS (MPa)	Elongation (%)	Necking (%)
1672	2028	13,1	33,3

Micrographs were made in the samples (Fig. 2), where the presence of martensite, bainite and carbides in the darker regions (grey and black) are noted, the light regions show portions of ferrite and retained austenite.

Cemented carbide inserts with ISO designation SNMA 120408 K10-20 grade, without a chip breaker, were used. The indexable inserts were mounted on an ISCAR toolholder, ISO code DSBNR 2525 M12. Although K grade cemented carbide is recommended for the turning of cast iron, this grade was selected due to its

accelerated wear on turning steels. A sample of the inserts were sent to the company Oerlikon Balzers where they received coatings. Some received a monolayer of AlCrN and others received a monolayer of nanostructured AlCrN, both applied by PVD with a thickness of 3 μm . The rest of the inserts remained uncoated in order to provide an experiment control. The AlCrN coating is usually deposited using the PVD technique and may be 1 to 5 μm thick. It has approximately microhardness of 1900 HV and an oxidation temperature above 700 $^{\circ}\text{C}$. The coating with AlCrN presents low barrier of thermal effect, medium resistance to the abrasion, medium resistance to the wear by the adhesion (when compared to the steel), medium resistance to wear by diffusion and presents medium protection of the substrate against corrosion [9].

The cemented carbide tools are divided into two main groups, one containing only tungsten carbide and cobalt (WC+Co) classified by DIN ISO 513 as K grade. K grade of Cemented carbide consists almost exclusively of unique tungsten carbides in a cobalt binder phase. It may also contain up to 0.8% of vanadium carbide (VC) mass and/or chromium carbide (Cr_3C_2) accompanied by up to 2% mass of tantalum and niobium carbide (TaC and NbC) as doping additives to control and stabilize grain size [15].

High abrasion resistance is a characteristic of the K grade carbide tools, but the strong tendency to diffuse of the tungsten carbide prevents the use of this type of tool in the machining of steels that produce long chips. These tools are recommended for machining cast iron and non-ferrous metals [16].

A physical acoustic piezoelectric transducer model R15i was used to acquire the acoustic emission data, along with a Spartan 2000 signal conditioner. The conditioned signals were acquired by a National Instruments PCI-6251 card, which has a maximum acquisition rate of 1.2 MS/s.

The sensor is 20.6 mm in diameter and 27 mm in height and was positioned on the specimen itself in the tensile tests and in the tool holder in the turning tests. Figure 3 shows the data acquisition diagrams for both tensile and turning tests.

The AE sensor was tested using the graphite breaking test where it demonstrates the sensor sensitivity and the excited frequency spectrum. This is recommended by the sensor manufacturer to test sensor validation.

The tool wear was measured by an optical stereomicroscope manufactured by Mitutoyo, model TM 15 with a micrometric screw with a resolution of 1 μm and a magnification of 15X. The adopted tool life criteria was based on ISO 3685, when the admissible flank wear is $\text{VB}_B \geq 0.3 \text{ mm}$ [16].

Since the AE signals acquired during machining are extremely sensitive to several types of excitation, including those associated with mechanisms of deformation and movement of defects, previous tensile tests were performed on the steel. In these tests, these excitations were monitored with acoustic emission sensors, to identify and separate the signals originating from deformation and from the tool wear mechanisms acting during machining. The tensile tests were performed with a claw displacement velocity (deformation rate) of 2 mm/s. This velocity was selected with the expectation that isolated

events generated by the phenomena responsible for the excitation of the steel could be detected. The tests were monitored using an acoustic emission sensor (AE) fixed to the useful length of the specimen. The AE data were acquired from the beginning of the elastic deformation until the rupture of the specimens.

Turning tests were performed using the following cutting conditions: cutting speeds (v_c) of 150 m/min, 200 m/min and 250 m/min; feed rates (f) of 0.10 mm/rev and 0.20 mm/rev; and depths of cut (a_p) of 0.25 mm and 0.75 mm, all under dry conditions and without the use of chip breakers. These parameters were selected because they represent conditions typically applied in the use of carbide tools on the shop floor.

The acoustic emission signals were collected by means of a piezoelectric sensor fixed to the tool-holder adding vaseline to increase transmissibility and acquisition software developed for this purpose on the Labview platform. The acquisition took place at a rate of 400 kHz (since continuous acquisition generates a large amount of data) and applying an active Butterworth high pass filter of 10 kHz. This filter was applied because below this frequency there is no signal generated by any exciter mechanism.

In the turning tests, the AE signals were collected for 2 s using software developed for this purpose on a two-stage Labview platform. The first set of signals was collected at the beginning of the pass and the second in the middle of the pass with a rate of 1.2 MHz (maximum limitation of the data acquisition board and the R15i sensor) and a 10 kHz active Butterworth high pass filter. Noise signals were collected before performed the tests to serve as a basis for eliminating noise in the collection signals using a suppressor filter.

In order to analyze the wear mechanisms, the tools were immersed in a solution of 30% hydrochloric acid in water for a period of 12 h to remove the adhered work material.

AISI 4340 steel turning tests were also conducted to characterize the machining signals and to compare them with the signals obtained in the tensile tests. In the turning tests, the three tools detailed previously were used.

The spectra obtained in the two tests (tensile test and turning) were compared and the main frequencies of the two signals were separated. The deformation and fracture frequencies of the steel were used to create a filter that would aid in the elimination of the signals originating from the cutting of the material during machining, thus leaving only the signals originating from the tool. The acoustic emission data were treated using software specially developed for this work and compared with the results for the other parameters evaluated.

After each pass, the flank wear of the tool was verified (measured and analysed using a stereomicroscope). As the purpose of the work was not to assign a technique to determine the tool end-of-life, what has already been done in another work [8], but to demonstrate the variation of excited frequencies over time, we only compared the start signals life and end of life.

Results And Discussion

Tensile Tests – Acoustic Emission

Since the acoustic emission (AE) signals were monitored throughout the tests, they could be compared with the stress-strain curve to extract the deformation phases present in the material from the time-domain AE signal. In the frequency spectrum corresponding to the elastic phase of the AISI 4340 steel (Fig. 4), the highest peak appears at a frequency of 150 kHz, followed by the peaks at 160 kHz, 170 kHz and 130 kHz.

The frequency spectrum of the plastic deformation phase of the AISI 4340 steel (Fig. 5) showed excitation at the same frequencies as the elastic deformation, but with reduced amplitudes. According to Physical Acoustics [14], the excitation frequency band of steel in the elastic phase lies in the region of 40 kHz to 200 kHz, whereas for the plastic phase excitation appears in the region of 350 kHz to 450 kHz. The fact that the amplitudes decreased but did not reach zero is due to the presence of a region of elastic deformation in the specimen.

The frequency spectrum for the fracture of the AISI 4340 steel (Fig. 6) shows one frequency range of 90 kHz to 110 kHz and another of 140 kHz to 155 kHz. The excitation band at 90 kHz to 110 kHz appeared in preliminary machining tests on other materials carried out by the authors. This indicates that its elimination could compromise the evaluation of wear mechanisms and phase changes. The band at 140 kHz to 155 kHz was used as the band-stop filter for the analysis of the AE data obtained in the turning tests, the elimination of this band resulting only in the signal related to the wear mechanisms.

Turning tests – Acoustic Emission

The short-time Fourier transform (STFT) technique is able to identify variations in the excitation mechanism, since it monitors the signals in both domains (time and frequency). This analysis is interesting, as it verifies whether there is any variation in the frequency over the data collection time, since the acoustic emission signal is highly dynamic and sensitive to the excitation mechanism.

Based on studies published in the literature, several mechanisms excite different frequencies in the spectrum of the AE signal. In machining, because of the dynamic cutting action, the tool undergoes wear and the formation of the chip varies the shape and the phase of the material causing a variation in the AE spectrum. The frequency range observed in machining is from 70 to 115 kHz [17]. White layer formation excite frequencies above 60 kHz [18]; isothermal phase transformation excites a frequency range from 250 to 350 kHz [19]; mild adhesive wear frequencies up to 120 kHz [20]; sliding from 25 to 110 kHz [21]; dislocation movement from 10 to 220 kHz [22]; particle interaction from 120 to 350 kHz [23]; abrasive wear from 200 to 1000 kHz [15, 24]; crack propagation from 350 to 550 kHz [1, 18]; phase transformation from 350 to 550 kHz [19]; vacancies accommodation from 220 to 380 kHz [25]; dislocation annihilation excites the AE signal on 100 kHz [4]; Frank-Read dislocation on 1000 kHz [4]; plastic deformation on 50

kHz [4] and from 150 to 500 kHz [22]; elastic deformation excite the AE signal in the range of 25 to 250 kHz [22] and thermal noise from 10 to 100 kHz [4].

Due to the various tribological mechanisms deriving from the wear of the tool and since these mechanisms operate at different frequencies, the acoustic emission signals in the turning tests are discrete and time variant. Thus, the use of STFT is a relevant option to demonstrate these mechanisms and their joint performance in the evolution of cutting tool wear.

In this work, STFT is used to detect and map the mechanisms which influence tool wear. Analyzing the STFT signal generated in the AE signal in turning AISI 4340 steel with a cutting speed of 250 m/min, feed rate of 0.25 mm/rev and depth of cut of 0.75 mm in a tool without end coating (Fig. 7), it is noted that the peak of greater amplitude is located in the frequency of 253kHz in the time of 0.75s. This is probably due to the interaction of particles since it is a K-class end-of-life tool in contact with steel, which denotes a diffusive mechanism. It is also noticed the frequency range of 90kHz to 170kHz excited during the entire period acquired from the diffusive mechanism and the movement of discordances. A line in the 35 kHz range is also excited and denotes sliding mechanisms. There is also a low amplitude range in the order of 200 kHz to 230 kHz which can be attributed to abrasive tool wear. This is consistent because an end-of-life tool suffers from high contact with the part and this provides the mechanism of diffusion. In order not to make the work large and repetitive, we chose to condense the images of the STFT signals into the plate shape (Fig. 8b) and compare the start and end of tool life signals.

In order to facilitate the demonstration of STFTs results, the 3 axes (time (x), frequency (y) and energy (z)) were unified in order to demonstrate the signals more clearly.

The STFTs of the acoustic emission signal obtained during the first turning pass with a cutting speed of 200 m/min, feed rate of 0.10 mm/rev and depth of cut of 0.25 mm are shown in Fig. 8. In Figs. 8a and 8b, the uncoated tool presented an STFT signal in which there is an excitation with irregular periodicity at frequencies of 222 kHz, 267 kHz, 314 kHz, 358 kHz, 403 kHz and 447 kHz, which are excited by the machine-tool spindle rotation (589 rpm). It can also be noted that the signal energy threshold is much higher (1150 mV) than that at the beginning of the tool life, where these two phenomena can be attributed to the chip entanglement in the part.

In Fig. 9c, a stimulus appears at between 1.575 s and 1.595 s, which repeats at between 1.756 and 1.774 s, with excitation in the frequency range of 138 kHz to 171 kHz. The highest energy frequency is at 150 kHz, which reaches an energy level of 1265 mV. High energy levels are also observed at the frequencies of 32 kHz and 30 kHz (545.5 mV and 542.5 mV, respectively). In the signal referring to the end of tool life of the AlCrN-coated tool (Fig. 9d), a decrease in the signal energy (peak of 454.20 mV) can be noted. The frequency with the highest energy is 32 kHz followed by 56.25 kHz. Excitation in the frequency range of 2 kHz to 98 kHz is observed throughout the signal acquisition period. In addition, there is excitation in the range of 232 kHz to 288 kHz, but with less energy than the previously mentioned range. The frequency ranges of 370 kHz to 468 kHz also shows excitation, which occurs over a period of 0.06 s with a range of

0.02 s, reaching a peak at 443 kHz. According to Hase et al. [7], at frequencies above 100 kHz excitation is due to crack propagation and particle interaction, which accelerates the tool wear mechanisms.

In the case of the AE signals for the nanostructured AlCrN-coated tool under intermediate machining conditions (Figs. 9e and 9f), it can be noted that in most cases there are two well-characterized excitation ranges: at 75 kHz to 105 kHz and at 389 kHz to 475 kHz. In the former frequency range the highest peak amplitude appears at 91 kHz in most of the signals obtained for these tools. Ferrer et al. [21] attribute this range to slip friction and Wada and Mizuno [22] to mild abrasive wear. By imposing a surface with a lower coefficient of friction, as demonstrated by Mo et al. [26] in their studies comparing AlCrN with other coatings, the tool begins to show sliding and soon after, by imposing force, abrasive wear and therefore excitation at this frequency is observed.

The range of 389 kHz to 475 kHz is characteristic of crack propagation [27] and medium-intensity abrasive wear [7]. During the cutting process the tool undergoes abrasive wear resulting in the beginning of crack formation and propagation, where there is a loss of material from the cutting edge of the tool, as is evident in Fig. 10. Grooves can be observed on the clearance surface (two-body abrasive wear characteristic) and porosity at the central end of the clearance surface (three-body abrasive wear characteristic). In the central region of the tool, characteristic surface fracture is noted.

Although the excited frequency bands demonstrate the prevalence of abrasive wear, the nanostructured AlCrN-coated tools show the best performance in terms of acoustic emission drivers. On comparing the STFTs of the signals for all of the tools studied, with a cutting speed of 200 m/min, a feed rate of 0.10 mm/rev and depth of cut of 0.25 mm, as shown in Fig. 9, it can be noted that the signal with the least change from the beginning to the end of the tool life is that with the nanostructured-AlCrN coating. This tool also presented a longer life.

Temperature may act as an attenuator of AE signal amplitude [28]. However, an increase in temperature contributes to a decrease in the resistance of the tool and this causes an increase in the wear, which is an AE signal generator. The fact that the cutting mechanism studied is severe (hard turning) and the geometry of the tool has negative angles of inclination and output, together with the cutting parameters, cause the temperature to rise and the tool loses resistance, suddenly altering the AE signal. In this situation, the AE signal indicates excitations at distinct frequencies over a short time interval. Figure 11 illustrates qualitatively (but not quantitatively because of the variation in the emissivity of the material due to the temperature variation) the difference in the temperature of the chip at two moments. Firstly (Fig. 11a), at the beginning of the chip entanglement in the workpiece, the temperature reaches a threshold lower than that at the moment where there is complete entanglement and the temperature of the chip increases (Fig. 11b). This causes the wear mechanisms, and consequently the acoustic emission signals to change.

At the beginning of the tests, using a cutting speed of 200 m/min, a feed rate of 0.20 mm/rev and a depth of cut of 0.75 mm (Fig. 12), the uncoated tool (Fig. 12a) shows excitation in the frequency range of 90 kHz to 110 kHz, a characteristic that is attenuated in the end-of-life signal for the tool. At a frequency of

109 kHz there was strong excitation in the period from 1.32 s to 1.35 s. This lies within the range of excitation frequencies associated with adhesive wear and adhesion-pull out mechanisms, the most predominant in the case of the uncoated tool. This is verified by Fig. 12a, where it can be noted that the tool without coating presents a lower amount of deposited material, being strongly influenced by adhesion-pull out, which later generates abrasive wear.

At the end of the tool life, for the uncoated tool (Fig. 12b) there is a decrease in the signal energy in relation to the signal generated at the beginning of the tool life (Fig. 12a). The increase in temperature and decrease in the rate of wear tend to promote this, since there is an association between the AE signals and the increase in temperature, with a decrease in the energy of the signals [28] and the rate of the excitation mechanisms. In addition, for the uncoated tool, the very characteristic peaks in the frequency range for the abrasive wear and crack propagation mechanisms (350 kHz to 460 kHz) observed at the beginning of the tool life (Fig. 12a) become more sparse in the signal obtained at the end of the tool life. This indicates that these phenomena occur mainly during the early part of the tool life.

Signals for the AlCrN-coated tool (Figs 12c and 12d) showed excitation in a wide frequency range of 2.34 kHz to 119.50 kHz, with sparse excitation across the entire frequency spectrum. The excitation observed up to 120 kHz is attributed to adhesive wear [22], dislocation and adhesion-pull out mechanisms. In the SEM micrographs (Fig. 13b), it can be noted that the tool has a large amount of workpiece material adhered on both the flank and rake surfaces. This corroborates the finding that the signals are in the frequency range associated with adhesive wear.

Figure 13d shows a strong influence of abrasive wear and crack propagation (frequency range 420 kHz to 470 kHz), which can be observed on the SEM micrograph of the tool (Fig. 13b) through the formation of chippings and crater wear. In addition, the signal includes the influence of adhesive wear and adhesion-pull out, with a decrease in the energy of the signal in relation to the beginning of the cut, this being influenced by the increase in temperature, which attenuates the signals.

The signals for the nanostructured AlCrN-coated tool (Figs. 12e and 12f) were practically the same at the beginning and end of the tool life. The signals are strongly influenced by adhesive wear and pull out (15 kHz to 115 kHz range) and by abrasive wear and crack propagation (350 kHz to 450 kHz). The signal for the nanostructured AlCrN-coated tool at the end of tool life (Fig. 12f) was attenuated, as was the signals for the other tools, due to the greater chip-tool-workpiece contact that generated higher temperature and thus attenuated the AE signals at the end of the tool life. This also increases the adhesion of the workpiece material to the tool, as shown in Fig. 13 ("a" to "c").

A cutting speed of 250 m/min, feed rate of 0.20 mm/rev and depth of cut of 0.75 mm was used as the maximum material removal rate (Figs. 14 and 15). The tools were able to perform only one pass before reaching the end-of-life criterion (0.6 mm of maximum flank wear) and the uncoated tool (Figs. 14a and 14b) showed the highest energy for the signal, indicating that the coating attenuates the tool degradation mechanisms during cutting. The uncoated tool excitation ranges were 32 kHz to 154 kHz and 375 kHz to

466 kHz for the beginning and end of the tool life, respectively. Note that the signals are practically the same under the two conditions, which indicates that at the beginning of the cut the tool is strongly affected by wear mechanisms and this continues until the end of the tool life.

The AlCrN-coated tool (Figs 14c 14d) shows excitation in a wide range of frequencies (2.3 kHz to 460 kHz) with a peak energy of 800 mV. As with the uncoated tool, for the AlCrN-coated tool the signals at the beginning and end of the tool life are practically the same, showing excitation in the period from 0.63 s to 1.23 s in the frequency range of 420 kHz to 423 kHz. This is associated with the excitation caused by the propagation of cracks or phenomena related to a phase change in the tool material, as reported by Hase et al. [7].

The nanostructured AlCrN-coated tool (Figs 14e and 14f) showed greater excitation in the ranges 10 kHz to 120 kHz and 320 kHz to 460 kHz when compared with the signals originated from uncoated tools. The first range corresponds to adhesive wear, pull out, and sliding while the second is related to abrasive wear and crack propagation. There was excitation at a frequency of 288 kHz throughout the cut for the tools coated with the AlCrN and nanostructured AlCrN. This frequency is associated with excitation by voids and particle interaction [22, 23, 29], which can be caused by the aggressiveness of the operation that causes this rearrangement in the coating structures.

The micrographs (SEM) in Fig. 15 show the clearance surfaces after turning with the coated tools. Figure 15a shows the presence of microcracks in the tool coated with AlCrN, which corroborates the appearance of excitation in the signal at the end of the tool life. As verified by Fig. 15b, no cracks are observed on the tool and abrasive wear is predominant.

Briefly, Table 2 sets the frequency ranges excited by the mechanisms observed in the tools.

Table 2. Wear Mechanisms and its AE frequencies in the turning.

Wear Mechanism	Frequency band observed
Adhesive wear	15 to 115 kHz
Sliding	35 kHz
Diffusion wear	40 to 120 kHz
Slip friction	75 to 105 kHz
Movement of dislocations	100 to 220 kHz
Abrasive wear	200 to 230 kHz
Particle Interaction	100 to 253 kHz
Crack propagation	420 to 470 kHz
Phase transformation	420 to 423 kHz

Conclusions

The results, analysis and discussion of the present investigation allowed the following conclusions to be drawn.

AE signals were used to detect mechanisms of abrasive action, cracking formation, slippage, dislocation movement, particle interaction and adhesion. This verifies the effectiveness of the technique in detecting defects in materials.

Because they are the same cutting tools (cemented carbide K class uncoated and coated by AlCrN), the AE signals excite the same set of frequencies. This is due to the fact that practically the same mechanisms act on all tools even varying the cutting parameters. Therefore, the behavior of the STFT signal occurred in the amplitudes of the excited frequencies.

In the study, frequencies were noted that responded as distinct mechanisms. The scientific community demonstrates that there are several phenomena acting in frequency bands that overlap. The physical responses to the phenomena were interpreted in the present work, taking into account SEM images. This is due to the fact of not fully understanding the acoustic emission signals.

Abrasion and adhesion wear mechanisms were most evident in the SEM images and they are well correlated with the AE signals. The frequencies relative to these mechanisms indicated in the literature and found in the present investigation corroborate to demonstrate that there is a map of excitation where each phenomenon presents a range of excitation in the spectrum of AE.

The STFT of the AE signals during turning showed that there is a large variation in the excitation frequencies during the cutting process, as expected since several wear mechanisms act at distinct moments and sometimes overlap abruptly, altering the behavior of the signals for the event detected applying the STFT technique.

In the turning tests, the use of techniques such as hit counters, means of signals and simple FFT are common but may present errors, since the signals change in a short period of time. Analysis using time-frequency techniques, such as STFT, demonstrated this. In addition, the STFT has shown that several mechanisms can act simultaneously and concomitantly on the tool along the machining process. The technique was found to be suitable for gathering knowledge on wear mechanisms as well as phenomena occurring during the machining of steels.

Declarations

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Figures

Figure 1

Map showing correlation of frequency spectra for AE with different phenomena [7].

Figure 2

Micrograph of the quenched AISI 4340 steel.

Tensile tests

Turning tests

Figure 3

AE sensor fixation diagram for tensile and turning tests.

Figure 4

AE signal due to elastic deformation of the AISI 4340 steel.

Figure 5

AE signal due to the plastic deformation of AISI 4340 steel.

Figure 6

AE signal due to fracture of AISI 4340 steel.

a) 3D signal view.

b) Front view.

Figure 7

STFT of the AE signal resulting from the turning of the AISI 4340 steel using uncoated tool, when machining under the following cutting conditions: cutting speed of 200 m/min, feed rate of 0.10 mm/rev and depth of cut of 0.25mm.

Figure 8

STFTs of the AE signals resulting from the turning of the AISI 4340 steel, when machining under the following cutting conditions: cutting speed of 200 m/min, feed rate of 0.10 mm/rev and depth of cut of 0.25mm.

Figure 9

SEM of surface of nanostructured AlCrN-coated tool nose after machining with a cutting speed of 200 m/min, feed rate of 0.10 mm/rev, depth of cut of 0.25 mm.

a) Beginning of the chip entanglement.

b) After the chip entanglement.

Figure 10

Thermographic images obtained during the turning of AISI 4340 steel with a cutting speed of 200 m min, feed rate of 0.10 mm/rev and depth of cut of 0.25 mm using an uncoated carbide tool.

Figure 11

STFTs of the AE signals resulting from the turning of AISI 4340 steel with a cutting speed of 200 m/min, feed rate of 0.20 mm/rev and depth of cut of 0.75mm.

Figure 12

STFTs of the AE signals resulting from the turning of AISI 4340 steel with a cutting speed of 200 m/min, feed rate of 0.20 mm/rev and depth of cut of 0.75 mm.

Figure 13

STFTs of the AE signal during the turning of the AISI 4340 steel with a cutting speed of 250 m/min, feed rate of 0.20 mm/rev and depth of cut of 0.75 mm.

a) AlCrN-coated tool.

b) Nanostructured AlCrN-coated tool.

Figure 14

SEM of the coated tools after turning AISI 4340 steel with a cutting speed of 250 m/min, feed rate of 0.20 mm/rev and depth of cut of 0.75 mm.